EXHIBIT B

General Thoracic Surgery

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Accurate indications, adverse reactions, and dosage schedules for drugs are provided in this book, but it is possible they may change. The reader is urged to review the package information data of the manufacturers of the medications mentioned.

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CHAPTER 103

ANATOMY OF THE ESOPHAGUS

Martin Rothberg, Scott Johnson, and Thomas R. DeMeester

RADIOGRAPHIC AND ENDOSCOPIC ANATOMY OF THE ESOPHAGUS

The esophagus starts as the continuation of the pharynx and ends at the cardia of the stomach. When the head is in normal anatomic position, the transition from pharynx to esophagus occurs at the lower border of the sixth cervical vertebra. Topographically, this corresponds to the cricoid cartilage anteriorly and the palpable transverse process of the sixth cervical vertebra laterally (Fig. 103–1). Flexion and extension of the neck shifts this point craniad or caudad by the length of one cervical vertebral body. After traversing the thorax and passing through the diaphragm, the esophagus terminates in the stomach at the level of the eleventh thoracic vertebra. The esophagus is firmly attached to the cricoid cartilage at its upper end and to the diaphragm at its lower end; during swallowing, these points of fixation move craniad the distance of one cervical vertebral body.

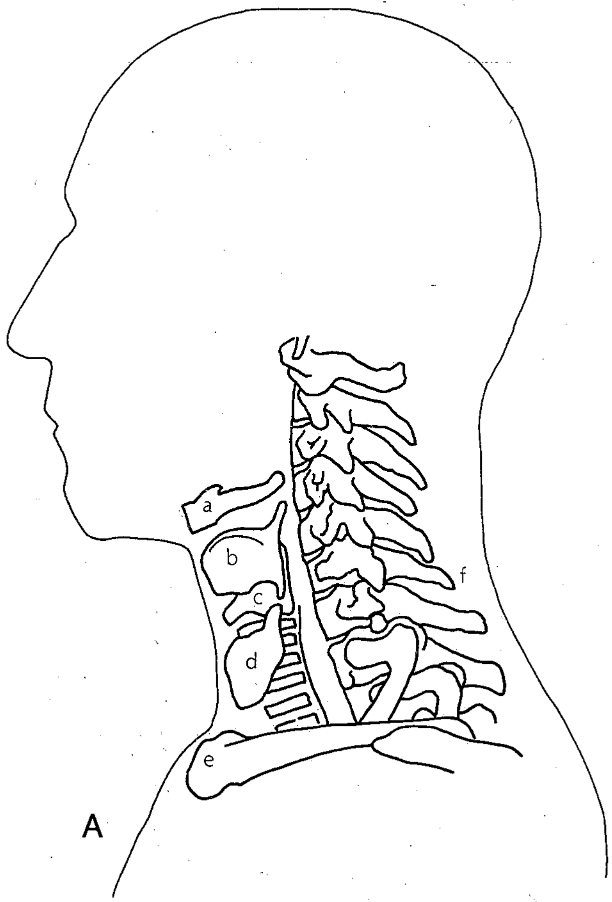
The configuration of the resting esophagus is determined by the contiguous structures it passes and the environmental pressure of the cavities it traverses. On a barium esophagogram, the cervical portion of the esophagus is flattened, owing to compression by adjacent structures; the thoracic portion is more rounded, owing to the negative intrathoracic pressure; and the abdominal portion is flattened, owing to the positive intra-abdominal pressure.

On the anteroposterior radiograph, the esophagus lies in the midline with a deviation to the left in the lower portion of the neck and upper portion of the thorax, and returns to the midline in the midportion of the thorax near the bifurcation of the trachea (Fig. 103–2A). In the lower portion of the thorax, the esophagus again deviates to the left to pass through the diaphragmatic hiatus.

On the lateral radiograph, the esophagus follows the curve of the vertebral column, except in the lower thoracic area where it curves anteriorly to pass through the diaphragmatic hiatus (Fig. 103–2B). The posterior curve and its terminal left anterior deviation is of importance in the performance of rigid esophagoscopy. The patient should be positioned to allow extension of the cervical and thoracic spine so that the rigid scope can be manipulated through this terminal arc. This region is the second most common site for traumatic esophageal perforation during rigid endoscopy, the first being the narrow entrance of the esophagus at the level of the cricopharyngeus.

Three normal areas of esophageal narrowing appear on the barium esophagogram and at esophagoscopy. The uppermost narrowing is located at the entrance into the esophagus and is caused by the cricopharyngeal muscle. Its luminal diameter is 1.5 cm and it is the narrowest point of the esophagus. The middle narrowing is the result of an indentation of the anterior and left lateral esophageal wall caused by the crossing of the left main stem bronchus and aortic arch. The luminal diameter at this point is 1.6 cm. The lowermost narrowing of the esophagus is at the hiatus of the diaphragm and is caused by the gastroesophageal sphincter mechanism. The luminal diameter at this point varies somewhat depending on the distention of the esophagus by the passage of food, but it has been measured at 1.6 to 1.9 cm. These normal constrictions tend to hold up swallowed foreign objects, and the overlying mucosa is subjected to injury by swallowed corrosive liquids because of their slow passage through these areas.

Measurements obtained during endoscopic examination (Fig. 103–3) show the average distance from the incisor teeth to the cardia of the stomach is 38 to 40 cm in men and generally 2 cm shorter in women. These distances are proportionately shorter in children, being 18 cm at birth, 22 cm at age 3 years, and 27 cm at 10 years. In men, the length of the esophagus from the cricopharyngeus muscle to the cardia ranges from 23 to 30 cm with an average of 25 cm. In women, the range is 20 to 26 cm with an average of 23 cm. The distance from the incisor teeth to the cricopharyngeus is 15 cm in men and 1 cm shorter in women. The bifurcation



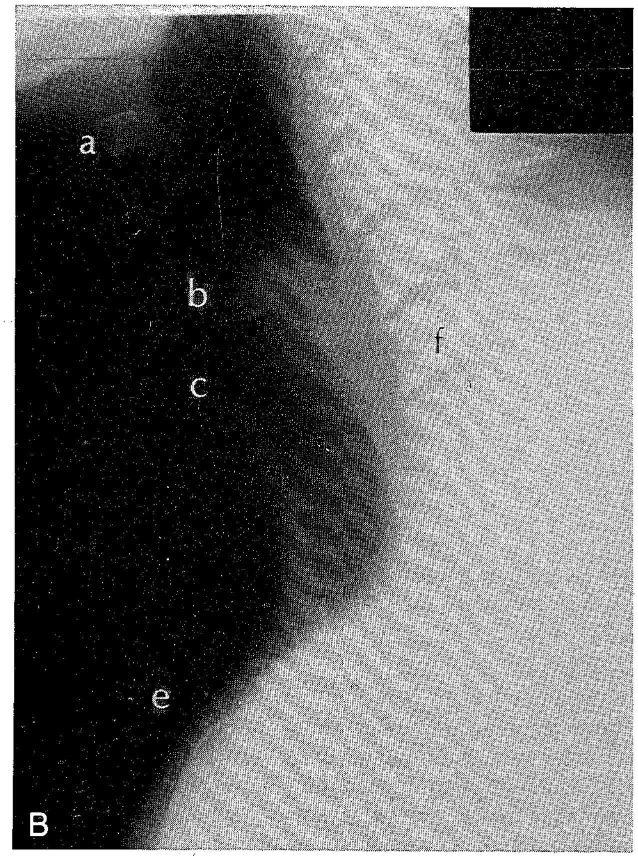


Fig. 103–1. *A*, Topographic relationships of the cervical esophagus: (a) hyoid bone, (b) thyroid cartilage, (c) cricoid cartilage, (d) thyroid gland, (e) sternomanubrial joint, (f) C6. *B*, Lateral radiographic appearance.

of the trachea and the indentation of the aortic arch ranges between 24 and 26 cm from the incisor teeth. It is helpful to locate an intraluminal lesion in reference to this landmark in order to decide on a left or right thoracotomy approach and to avoid interference from the aortic arch.

Manometrically, the length of the esophagus between the lower border of the cricopharyngeus and upper border of the lower sphincter varies according to the height of the individual. Figure 103–4 shows a nomogram for esophageal length based on height.

RELATIONSHIP OF THE ESOPHAGUS TO THE HYPOPHARYNX

The esophagus serves as a conduit between the pharynx and the stomach. As such, the esophagus represents an extension of the hypopharynx beginning at the lower border of the larynx at the level of the sixth cervical vertebra. The pharyngeal musculature consists of three overlapping, broad, flat, fan-shaped constrictors (Fig. 103–5). They are the superior constrictor arising mainly from the medial pterygoid plate, the middle constrictor arising from the hyoid bone, and the inferior constrictor arising from the thyroid and cricoid cartilages. These muscles insert with their corresponding muscle from the opposite side into a median posterior raphe.

The opening of the esophagus is collared by the cricopharyngeal muscle, which arises from both sides of the cricoid cartilage of the larynx and forms a continuous transverse muscle band without an interruption by a median raphe. The fibers of this muscle blend inseparably with those of the inferior pharyngeal constrictor above and the inner circular muscle fibers of the esophagus below. Thus, some investigators believe that the cricopharyngeus is part of the inferior constrictor; that is, the inferior constrictor has two parts, an upper or retrothyroid portion having diagonal fibers, and a lower or retrocricoid portion having transverse fibers. Keith (1910) has shown that these two parts of the same muscle serve totally different functions. The retrocricoid portion serves as the upper sphincter of the esophagus and relaxes when the retrothyroid portion contracts to force the swallowed bolus from the pharynx into the esophagus.

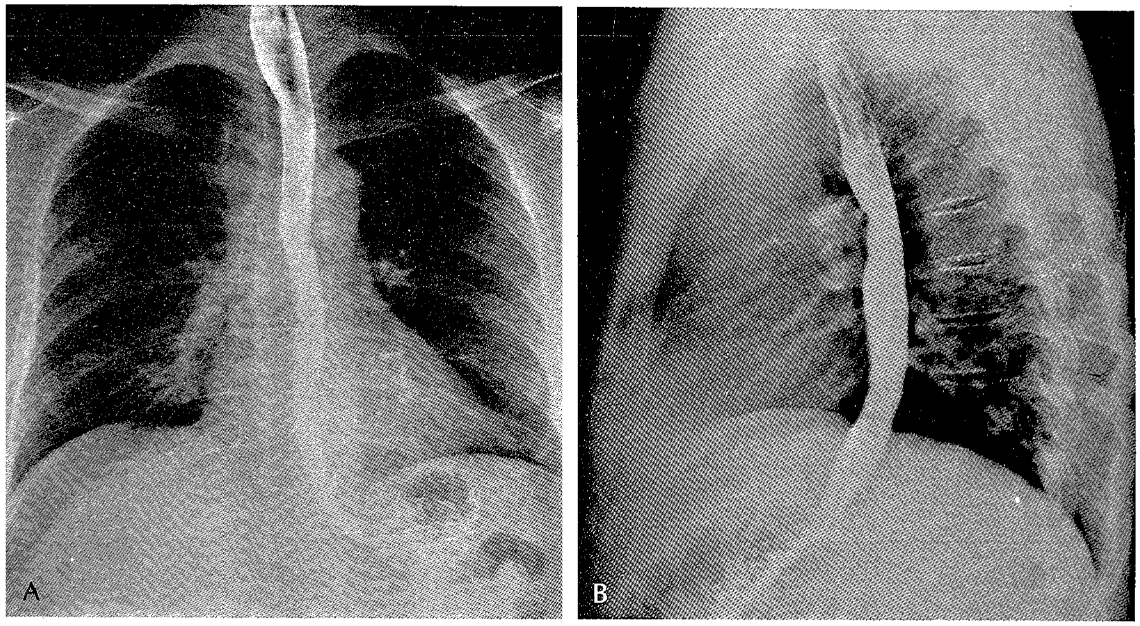


Fig. 103–2. Barium esophagogram. *A*, Anteroposterior view. *B*, Lateral view.

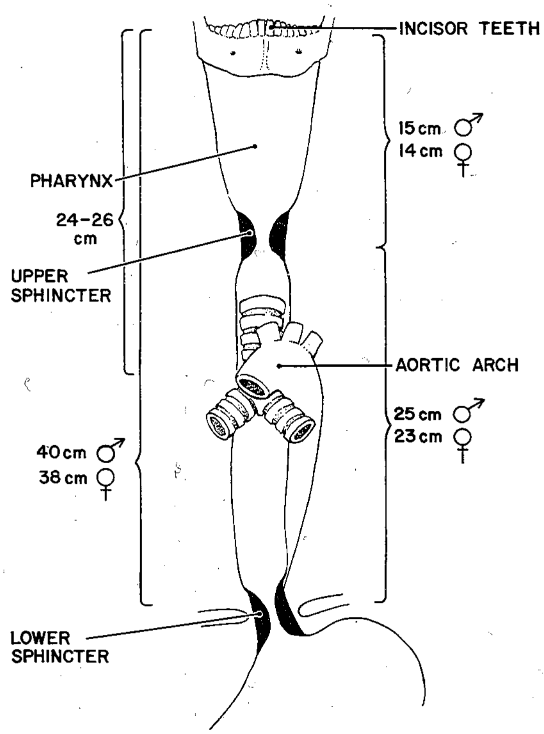


Fig. 103–3. Important clinical endoscopic measurements of the esophagus in adults.

RELATIONSHIP OF THE CERVICAL ESOPHAGUS TO STRUCTURES AND FASCIAL PLANES OF THE NECK

The cervical portion of the esophagus is approximately 5 cm long and descends between the trachea and the vertebral column from the level of the sixth cervical vertebra to the level of the interspace between the first and second thoracic vertebrae posteriorly, or the suprasternal notch anteriorly. It is separated from the posterior wall of the trachea by loose fibrous tissue, and from the prevertebral fascia by loose alar fascia. The recurrent laryngeal nerves lie in the right and left grooves between the trachea and the esophagus. The left recurrent nerve lies somewhat closer to the esophagus than the right owing to the slight deviation of the esophagus to the left and the more lateral course of the right recurrent nerve around the right subclavian artery. Laterally, on the left and right side of the esophagus, are the carotid sheaths and the lobes of the thyroid gland.

Anteriorly, the cervical esophagus and trachea are bounded by the pretracheal fascia, which splits to envelop the thyroid gland, then continues down to the aortic arch. Posteriorly, both are bound by the prevertebral fascia, and laterally by the fascia forming the carotid sheath (Fig. 103–6). The buccopharyngeal fascia, which lies over the posterior pharyngeal muscles, extends inferiorly, directly on the posterior wall of the esophagus and laterally to the carotid sheaths, and separates the esophagus from the prevertebral fascia. These fascial planes form two spaces: a paraesophageal space containing the thyroid gland, larynx, trachea, and part of the pharynx, and a retroesophageal space. This latter space is continuous with the retroesophageal space

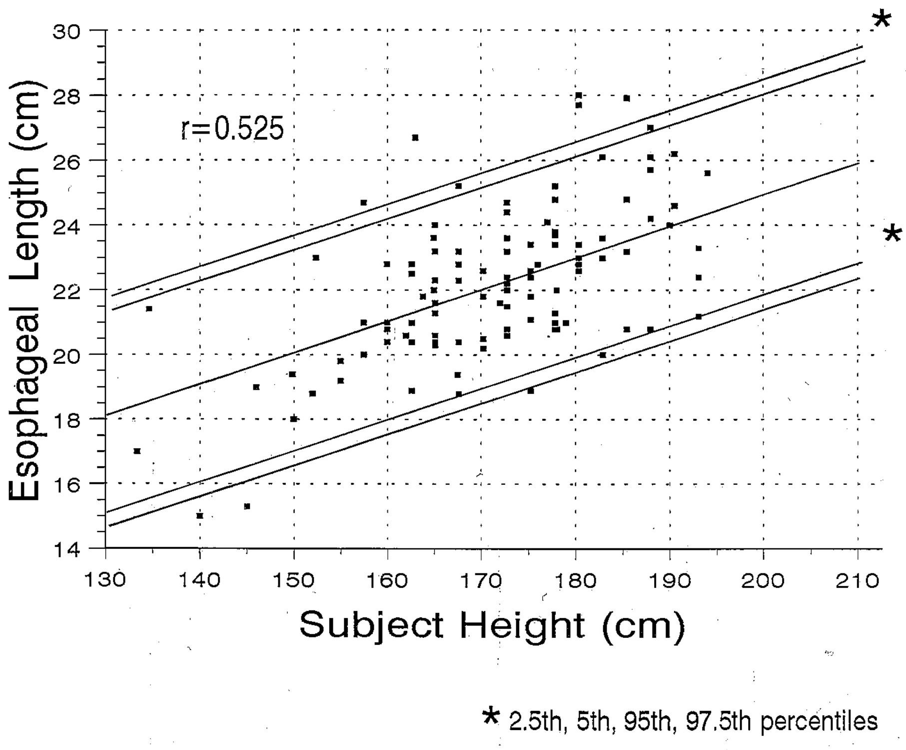


Figure 103–4. Nomogram of subject height versus esophageal length.

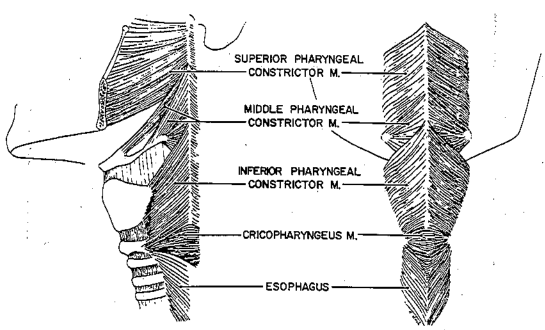


Fig. 103–5. External muscles of the pharynx.

at the base of the skull above and the superior mediastinum below. These spaces allow an access for extension of infection into the mediastinum.

RELATIONSHIP OF THE THORACIC ESOPHAGUS TO MEDIASTINAL STRUCTURES

The thoracic portion of the esophagus is approximately 20 cm long and starts at the thoracic inlet. From the thoracic inlet to the tracheal bifurcation, the thoracic esophagus remains in intimate relationship with the posterior wall of the trachea and the prevertebral fascia. Just above the tracheal bifurcation, the esophagus passes to the right of the aorta. This anatomic positioning can cause a notch indentation in its left lateral wall on a barium swallow radiograph. Immediately below this notch, the esophagus crosses both the bifurcation of the trachea and the left main stem bronchus, owing to the slight deviation of the terminal portion of the trachea to the right by the aorta (Fig. 103–7). From there down, the esophagus passes over the posterior surface of the subcarinal lymph nodes, and then descends over the pericardium of the left atrium to reach the diaphragmatic hiatus (Fig. 103–8).

The right lateral surface of the thoracic esophagus is completely covered by the parietal pleura, except at the level of the fourth thoracic vertebra where the azygos vein turns anteriorly over the esophagus to join the superior vena cava. The left lateral surface of the upper portion of the thoracic esophagus is covered anterolaterally by the left subclavian artery and posterolaterally by the parietal pleura. The distal portion of the esophagus, from the aortic arch down, lies to the right of the descending thoracic aorta. At the level of the eighth thoracic vertebra, the aorta disappears behind the esophagus, and its left lateral wall is covered only with the parietal pleura of the mediastinum and is the common site of perforation in Boerhaave's syndrome. From the bifurcation of the trachea downward, both the vagal nerves and the esophageal nerve plexus lie on the muscular wall of the esophagus.

Posteriorly, the thoracic esophagus follows the curvature of the spine and remains in close contact with the vertebral bodies (Figs. 103–7 and 103–8). From the eighth thoracic vertebra downward, the esophagus moves ventrally away from the spine and passes through the esophageal hiatus of the diaphragm in front of the

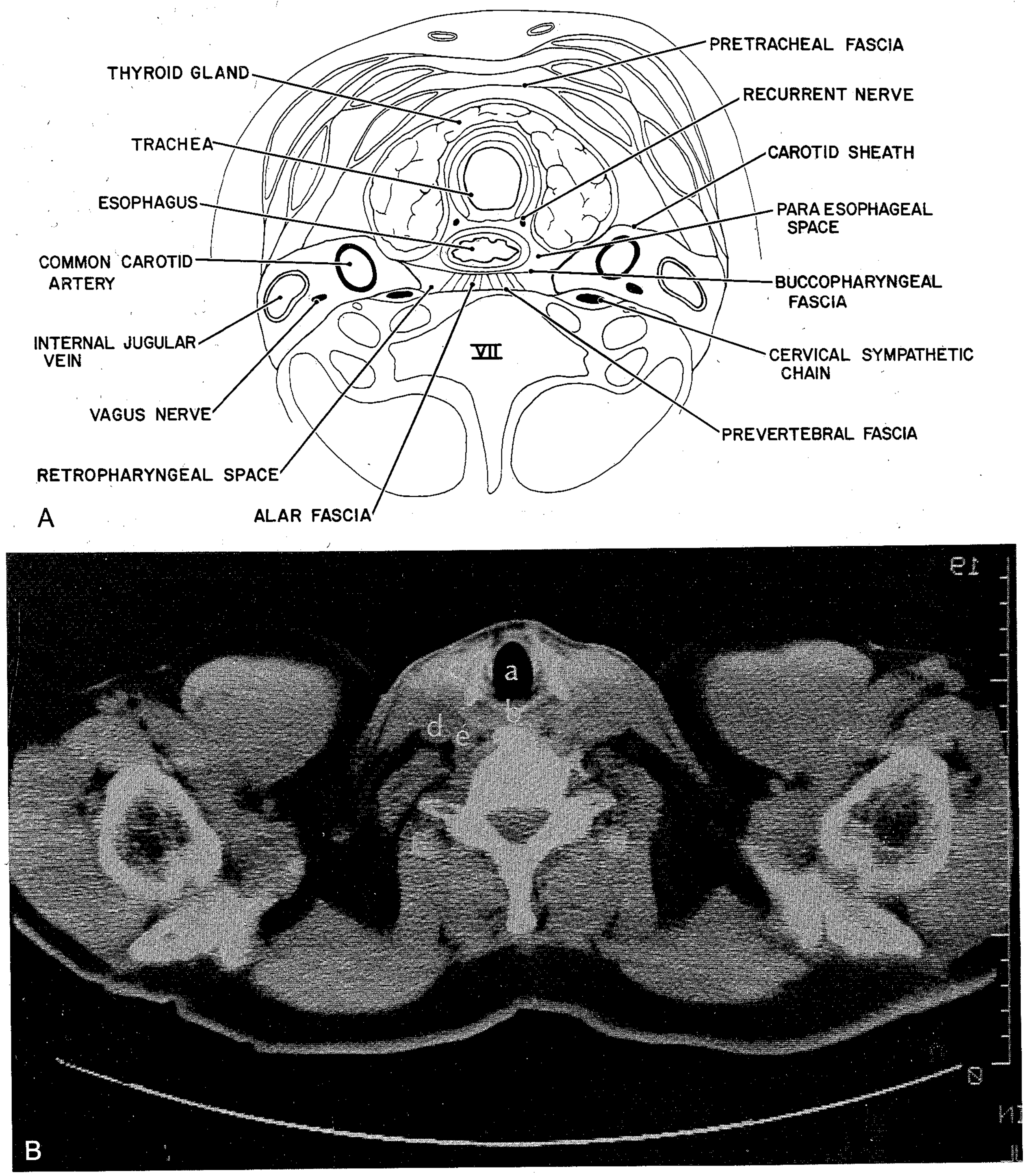


Fig. 103–6. *A*, Cross section of the neck at the level of the thyroid isthmus. *B*, CT appearance viewed from above: (a) trachea, (b) esophagus, (c) left thyroid lobe, (d) internal jugular vein, (e) common carotid artery.

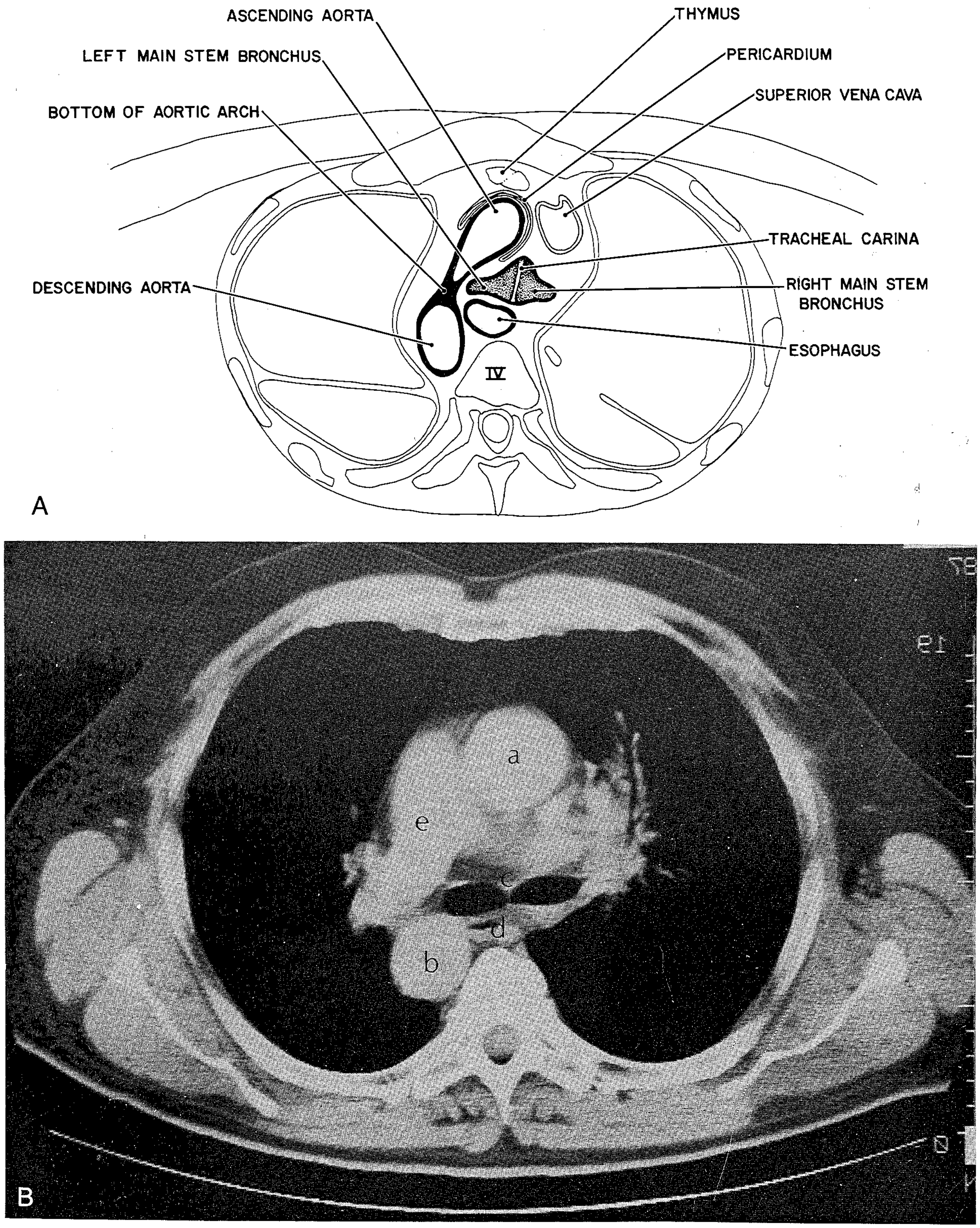
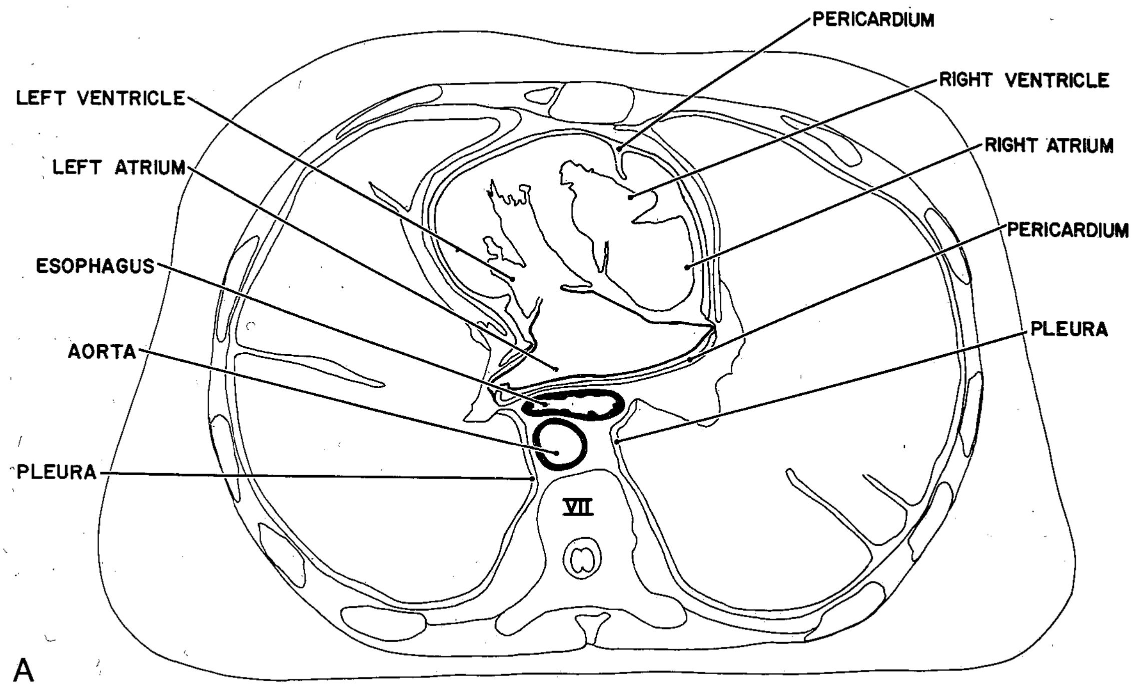


Fig. 103–7. *A*, Cross section of the thorax at the level of the tracheal bifurcation. *B*, CT appearance viewed from above: (a) ascending aorta, (b) descending aorta, (c) tracheal carina, (d) esophagus, (e) pulmonary artery.



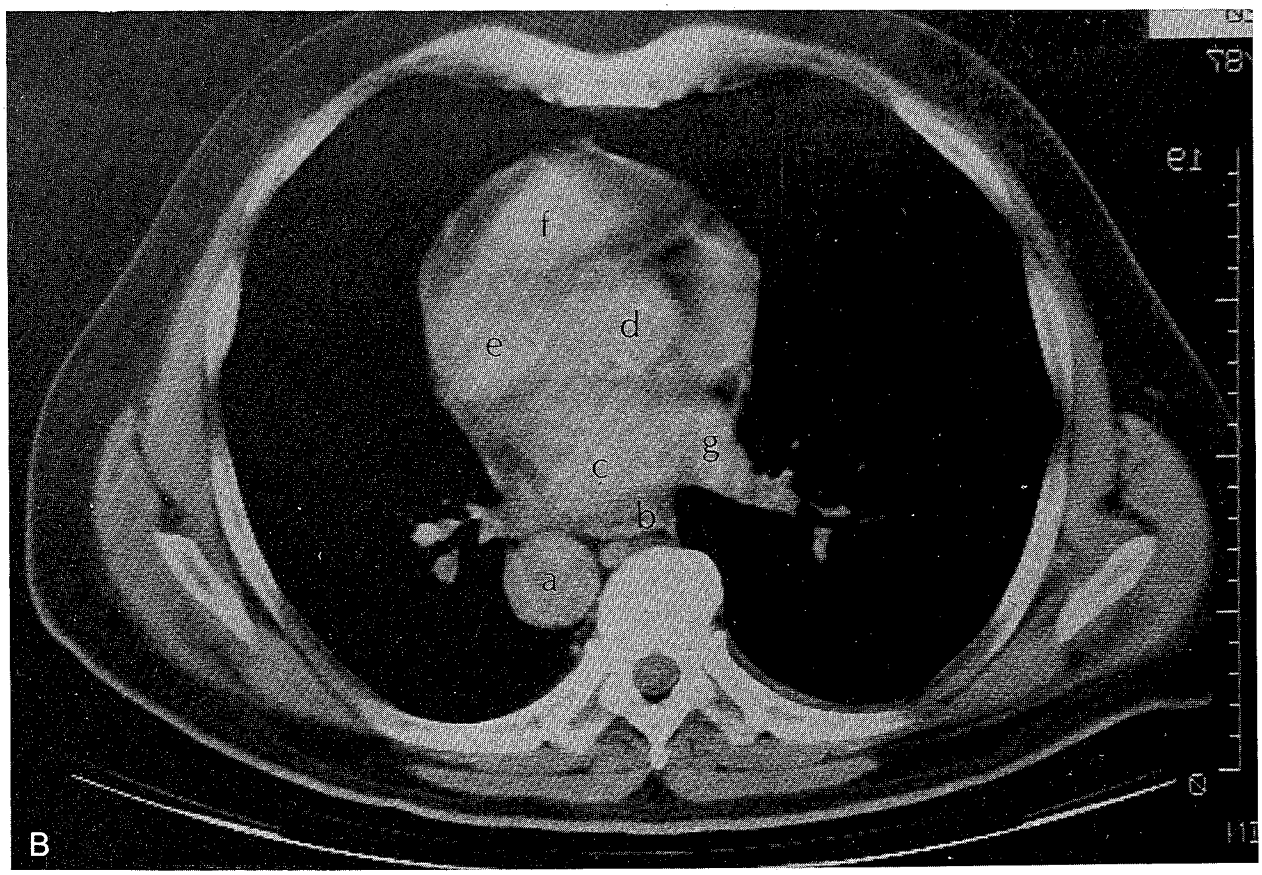


Fig. 103–8. *A*, Cross section of the thorax at mid-left arterial level. *B*, CT appearance viewed from above: (a) aorta, (b) esophagus, (c) left atrium, (d) right atrium, (e) left ventricle, (f) right ventricle, (g) pulmonary vein.

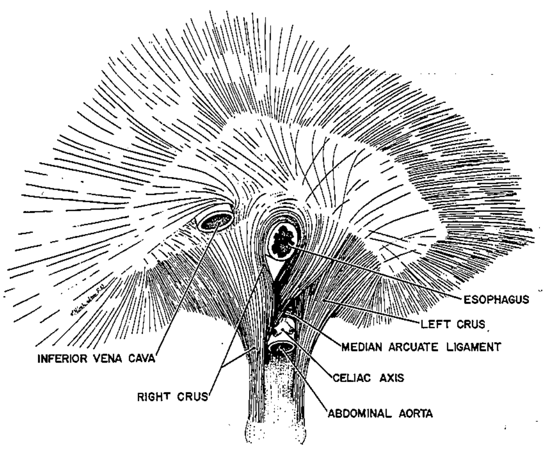


Fig. 103–9. The diaphragm and esophageal hiatus seen from below.

aorta (Fig. 103–9). The inferior vena cava, while not in apposition to the esophagus, lies anterior and to its right. Dorsally, the esophagus is crossed by the first five intercostal arteries and the hemiazygos vein. The thoracic duct passes through the hiatus of the diaphragm on the anterior surface of the vertebral column behind the aorta and under the right crus. In the thorax, it lies dorsal to the esophagus between the azygos vein on the right and the descending thoracic aorta on the left. From the level of the fifth thoracic vertebra upward, the thoracic duct gradually moves to the left and settles between the esophagus and the left parietal pleura, dorsal to the aortic arch and the intrathoracic part of the subclavian artery. In the neck, it turns away from the esophagus and joins the venous system at the junction of the subclavian and internal jugular veins.

RELATIONSHIP OF THE TERMINAL ESOPHAGUS TO THE DIAPHRAGMATIC HIATUS AND STOMACH

The muscular fibers forming the crura of the diaphragm arise by tendinous bands from the anterolateral surface of the first three or four lumbar vertebrae and their intervening fibrocartilages (Fig. 103–9). The right crus is longer and thicker than the left and the inferior extension of its fibers gives rise to the ligament of Treitz. The upper abdominal aorta lies at the base of the diaphragmatic hiatus just anterior to the vertebral bodies. The celiac and superior mesenteric arteries, as they arise from the upper abdominal aorta, separate the muscle bundles of the right and left crura. In many situations, a well-marked median arcuate ligament or tendinous rim of the diaphragm unites the two crura anterior to the aorta just above the celiac artery. The cadaver dissections described by Lindner and Kemprud (1971) show that in most situations, the median arcuate ligament was a firm, well-defined ligamentous structure, but in several cadavers, it was difficult to identify any definite connective tissue structure.

As the right crus ascends, it divides into a superficial and deep muscle layer. The superficial layer, by a gradual anterior curve, forms the muscular rim of the right edge of the esophageal hiatus. The deep layer inclines obliquely to the left over the anterior surface of the abdominal aorta and then ascends to form the left margin of the esophageal hiatus. The left crus ascends vertically against the fibers to the left margin of the hiatus. This anatomy is found in only about 46% of individuals, and marked variability exists. The most common anatomic variant is a shift to the left of various degrees, depending on the extent to which the margins of the hiatus are formed by muscle fibers from the left crus.

As the esophagus passes through the diaphragmatic hiatus, it is surrounded by the phrenoesophageal membrane, a fibroelastic ligament arising from the subdiaphragmatic fascia as a continuation of the transversalis fascia lining the abdomen (Fig. 103–10). The phrenoesophageal membrane divides at the lower margin of the esophageal hiatus into a stout, elongated ascending leaf that surrounds the terminal segment of the esophagus in tentlike fashion, and into a shorter, thin, descending leaf, which merges as the visceral peritoneal covering of the stomach. The upper leaf of the membrane attaches itself circumferentially around the esophagus, about 1 to 2 cm above the level of the hiatus. Between the upper leaf of the membrane and the cardia is a ring of fatty tissue interspersed with fibers from the lower leaf of the membrane. These fibers blend in with the elastic-containing adventitia of the distal 2 cm of the esophagus and the cardia of the stomach. This makes up the abdominal portion of the esophagus and is subjected to the positive pressure environment of the abdomen.

At the gastroesophageal junction, the outer longitudinal muscle fibers of the esophagus are continuous with the outer longitudinal muscle fibers of the stomach, and the inner circular fibers of the esophagus interlace with and are eventually replaced by the inner oblique gastric fibers that arise in the direction of the gastric fundus (Fig. 103–11). For a distance of 1.5 cm caudad

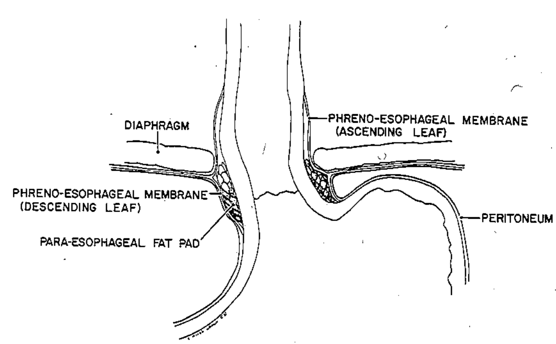


Fig. 103–10. Attachments and structure of the phrenoesophageal membrane.

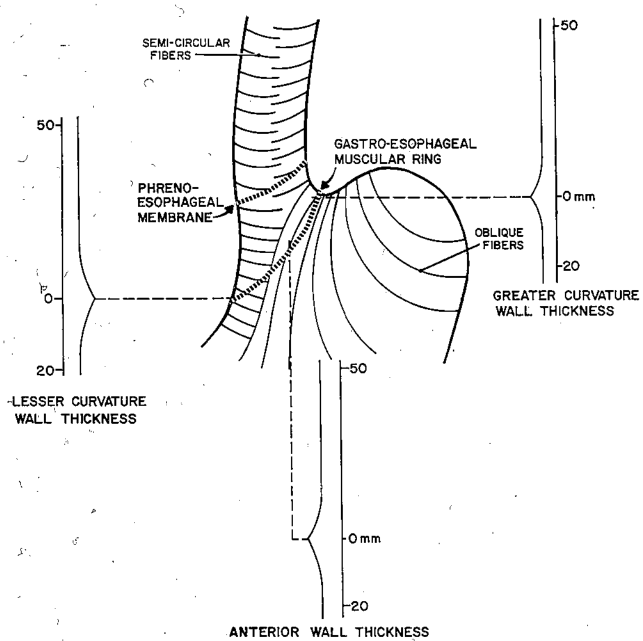


Fig. 103–11. The inner muscular fiber arrangement, and muscular thickness at the cardia. Adapted *from* Lieberman-Meffert D, et al: Muscular equivalent of the lower esophageal sphincter. Gastroenterology 76:31, 1979.

from the insertion of the upper phrenoesophageal membrane, the muscular wall of the cardia gradually becomes thicker because of increased density of the esophageal circular musculature on the lesser curvature side and the gastric oblique musculature on the greater curvature side. The line of maximal muscular thickness has an oblique orientation so that, on the greater curvature side, it is more cephalad than on the lesser curvature side. It is also asymmetric in that the muscle mass on the side of the greater curvature is larger (Fig. 103–11). The function of this asymmetric oblique muscle thickening is difficult to determine, but Liebermann-Meffert and associates (1979) pointed out some relationships of interest. The manometrically defined, distal esophageal high pressure zone is located in this area, and the length of the high pressure zone is similar to that of the thickening. The highest pressure in the high pressure zone is found in the area of the greatest thickening, that is, on the side of the greater curvature of the stomach. Therefore, this muscle thickening might, at least in part, coincide with the lower esophageal sphincter. Some authors ascribe to this muscular arrangement a role in the anti-reflux mechanism. Other factors contributing to the closing mechanism of the cardia are: the intra-abdominal portion of the esophagus, the rosette-like configuration of the gastric mucosa around the orifice of the cardia, the sharp angle between the lower esophagus and the gastric fundus, and the phrenoesophageal membrane and its configuration with the esophageal hiatus at the diaphragm. None of these latter structures, however, can be considered to function as a definite anatomic sphincter.

MUSCULATURE OF THE ESOPHAGUS

The musculature of the esophagus can be divided into an outer longitudinal and an inner circular layer. The upper 2 to 6 cm of the esophagus contains only striated muscle fibers. From there on, smooth muscle fibers gradually become more abundant, and at a distance of 4 to 8 cm from the superior end, or at the junction of the upper and lower two thirds, the smooth musculature constitutes 50% of the esophageal muscle. The transition of striated to smooth muscle in the inner circular layer is at a higher level than in the outer longitudinal layer. Most of the clinically significant esophageal motility disorders involve only the smooth muscle in the lower two thirds of the esophagus. When a surgical esophageal myotomy is indicated, the incision usually needs only to extend this distance.

The longitudinal muscle fibers originate from a cricoesophageal tendon arising from the dorsal upper edge of the anteriorly located cricoid cartilage. The two bundles of muscles diverge and meet in the midline on the posterior wall of the esophagus about 3 cm below the cricoid (see Fig. 103–5). From this point on, the entire circumference of the esophagus is covered by a layer of longitudinal muscle fibers. This configuration of the longitudinal muscle fibers around the most proximal part of the esophagus leaves a V-shaped area in the posterior wall covered only with circular muscle fibers. In the upper one third of the esophagus, the longitudinal muscle layer is thicker on the lateral surface than on the ventral or dorsal surfaces. In the lower two thirds, the longitudinal layer becomes more uniform and its overall thickness decreases distally. The course of the longitudinal muscle fibers is that of an elongated spiral, turning to the left around one quarter of the esophageal circumference — 90° — as they descend.

The circular muscle layer of the esophagus is thicker than the outer longitudinal layer. These fibers run horizontally only in the isolated and retracted esophagus. In situ, their course is elliptic and spiral with an inclination that varies according to the level of the esophagus: in the cervical portion, the highest point of the ellipse is dorsal; in the upper thoracic portion, the highest point is right lateral, behind the heart ventral; and in the abdomen, the fibers are horizontal. The arrangement of both the longitudinal and circular muscle fibers makes the peristalsis of the esophagus assume a wormlike drive as opposed to segmental and sequential squeezing. As a consequence, severe motor abnormalities of the esophagus assume a corkscrew-like pattern on the barium swallow radiograph.

ARTERIAL BLOOD SUPPLY OF THE ESOPHAGUS

The cervical portion of the esophagus receives its main blood supply from the inferior thyroid artery with smaller accessory branches from the common carotid, subclavian and superficial cervical arteries. The thoracic portion receives its blood supply from the bronchial

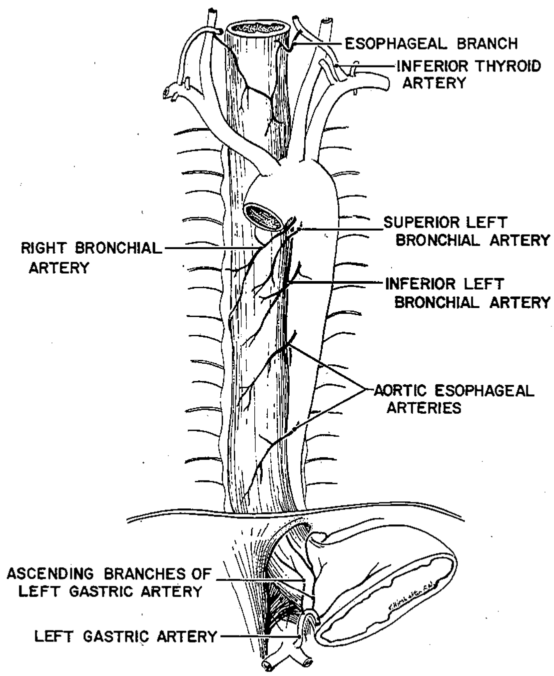


Fig. 103–12. Arterial blood supply of the esophagus.

arteries with 75% of individuals having one right-sided and one or two left-sided branches. Two esophageal branches arise directly from the aorta. The upper branch is usually the shorter and originates at the level between the sixth and seventh thoracic vertebrae; the lower is longer and originates at the level between the eighth and ninth thoracic vertebrae. The abdominal portion of the esophagus receives its blood supply mainly from esophageal branches of the left gastric and inferior phrenic arteries (Fig. 103–12). On entering the wall of the esophagus, the arteries assume a T-shaped division to form longitudinal anastomoses, giving rise to an intramural vascular network in the muscular and submucosal layers. As a consequence, the esophagus can be mobilized from the stomach to the level of the aortic arch without fear of devascularization and ischemic necrosis. Caution should be exercised as to the extent of esophageal mobilization in patients who have had a previous thyroidectomy and ligation of the inferior thyroid arteries proximal to the origin of the esophageal branches.

VENOUS DRAINAGE OF THE ESOPHAGUS

Blood from the capillaries of the esophagus flows into a submucosal venous plexus and then into a periesophageal venous plexus from which the esophageal veins originate. In the cervical region, the esophageal veins empty into the inferior thyroid vein; in the thoracic region, into the bronchial, azygos, or hemiazygos veins; and in the abdominal region, into the coronary vein (Fig. 103–13). The submucosal venous networks of the esophagus and stomach are in continuity with each

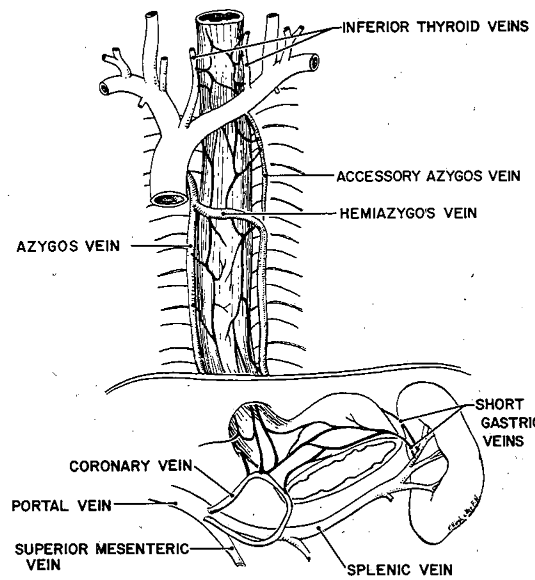


Fig. 103–13. Venous drainage of the esophagus.

other, and in patients with portal venous obstruction, this communication functions as a collateral pathway for portal blood to enter the superior vena cava via the azygos vein.

NERVE SUPPLY OF THE ESOPHAGUS

The constrictor muscles of the pharynx receive branches from the pharyngeal plexus, which is on the posterior lateral surface of the middle constrictor muscle and is formed by pharyngeal branches of the vagus nerves, with a small contribution from the ninth and eleventh cranial nerves (Fig. 103–14).

The complete parasympathetic innervation of the esophagus is provided by the vagus nerves. The cricopharyngeal sphincter and the cervical portion of the esophagus receive branches from both recurrent laryngeal nerves, which originate from the vagus nerves; the right recurrent nerve at the lower margin of the subclavian artery, the left at the lower margin of the aortic arch. They are slung dorsally around these vessels and ascend in the groove between the esophagus and trachea, giving branches to each. Damage to these nerves not only interferes with the function of the vocal cords, but also interferes with the function of the cricopharyngeal sphincter and the motility of the cervical esophagus, causing a predisposition to pulmonary aspiration on swallowing.

The upper thoracic esophagus receives branches from the left recurrent laryngeal nerve and directly from both vagus nerves as they descend through the superior mediastinum. The lower thoracic esophagus is innervated by the esophageal plexus located directly on both the anterior and posterior esophageal wall and formed by both vagal nerves after they pass behind the hilum of the lung and turn medially to reach the esophagus.

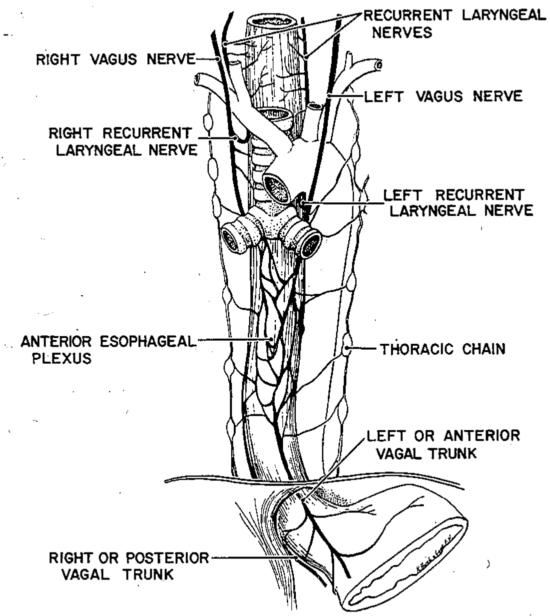


Fig. 103–14. Innervation of the esophagus.

The esophageal plexus also receives fibers from the thoracic sympathetic chain. The left vagus nerve splits before the esophageal plexus to form two branches: the first branch runs through the ventral esophageal plexus and constitutes the main element of the anterior or left abdominal vagal trunk; the second branch runs around the left esophageal wall, to join the dorsal esophageal plexus, and contributes to the formation of the posterior or right abdominal vagal trunk. As a result of the intertwining of fibers from both the left and right vagus in the esophageal plexus, both the left or anterior and right or posterior abdominal vagal trunks contain fibers of the original left and right vagus. The average distance above the diaphragm at which the left or anterior vagal trunk becomes a single nerve is 5.13 cm, and the right or posterior vagal trunk is 3.7 cm.

The preganglionic sympathetic fibers supplying the esophagus take origin from the fourth to the sixth spinal cord segments and terminate in the cervical and thoracic sympathetic ganglions. The pharyngeal plexus receives sympathetic fibers that arrive directly from the superior cervical ganglion via vagal nerves. The postganglionic fibers reach the esophagus via nerve branches that veer off from the cervical and thoracic sympathetic chain: some reach the esophageal wall directly, others join the vagal trunks. Thus, the vagal nerves caudad from their entrance into the neck always contain a number of postganglionic sympathetic fibers. The distal esophageal segments also receive direct sympathetic fibers coming from the celiac ganglion. These fibers reach the esophagus via the periarterial plexus around the left gastric and phrenic arteries.

Afferent visceral sensory pain fibers from the esophagus end without synapse in the first four segments of the thoracic spinal cord by using a combination of sympathetic and vagal pathways. These pathways are also occupied by afferent visceral sensory fibers from the heart; hence, both organs have similar symptomatology.

LYMPHATIC DRAINAGE OF THE ESOPHAGUS

The detailed lymphatic anatomy of the esophagus and its lymphatic drainage is discussed in Chapter 104.

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